U.S. SunShot Program and Grid Integration Overview

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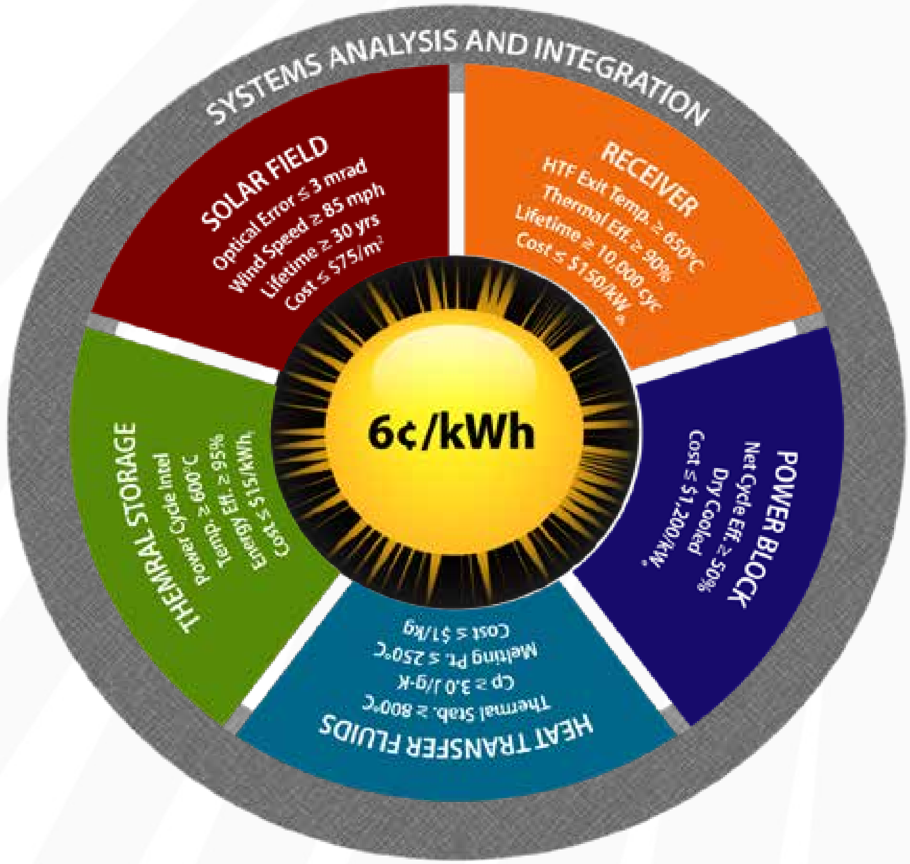
Discussion

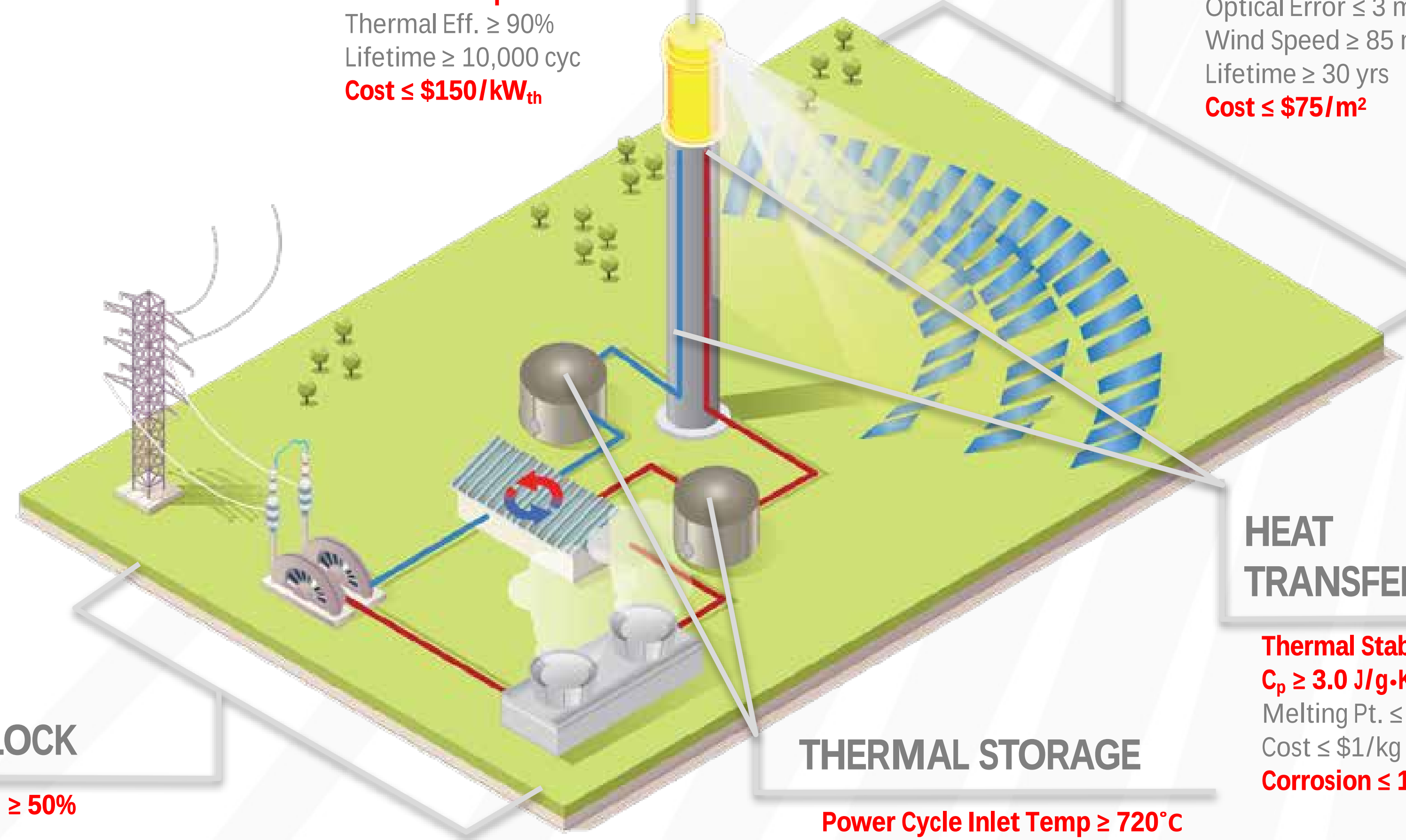
- U.S. SunShot Overview
- Understanding the Value of CSP with Thermal Energy Storage

U.S. DOE SunShot Initiative – Concentrating Solar Power

- SunShot initiated in 2012
- Identified technology and cost objectives to achieve 6¢ LCOE target:
    - solar field
    - receiver
    - thermal storage/HTF
    - power block



CSP Program Technical Targets



RECEIVER

HTF Exit Temp ≥ 720˚C
Thermal Eff. ≥ 90%
Lifetime ≥ 10,000 cyc
Cost ≤ $150/kW$_{th}$

SOLAR FIELD

Optical Error ≤ 3 mrad
Wind Speed ≥ 85 mph
Lifetime ≥ 30 yrs
Cost ≤ $75/m^2

HEAT TRANSFER FLUID

Thermal Stab. ≥ 800˚C
C_p ≥ 3.0 J/g·K
Melting Pt. ≤ 250˚C
Cost ≤ $1/kg
Corrosion ≤ 15 µm/yr

POWER BLOCK

Net Cycle Eff. ≥ 50%
Dry Cooled
Cost ≤ $900/kW$_e$

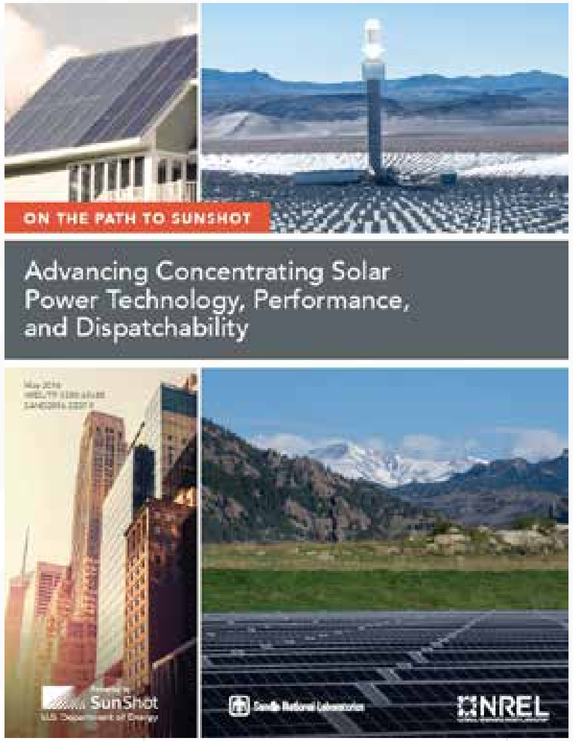
THERMAL STORAGE

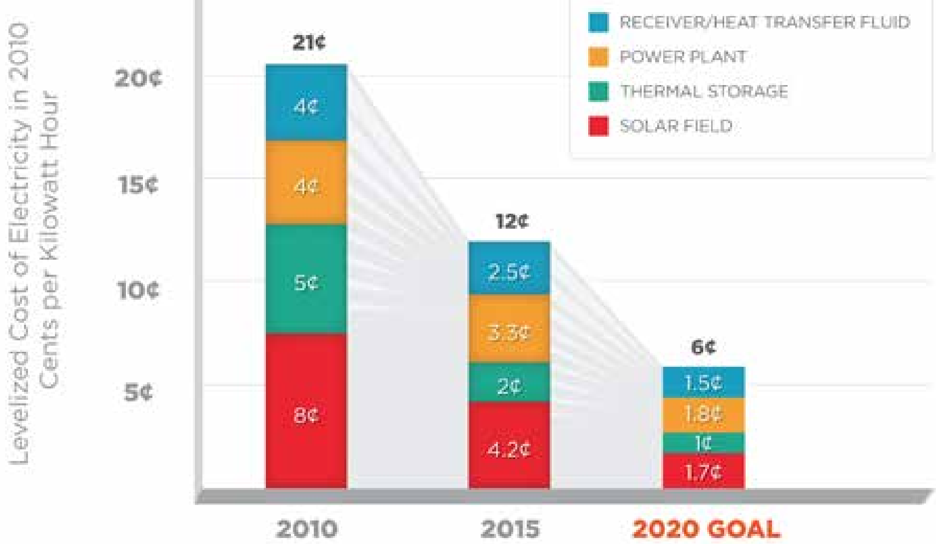
Power Cycle Inlet Temp ≥ 720˚C
Energy Eff. ≥ 99%
Exergy Eff. ≥ 95%
Cost ≤ $15/kWh$_{th}$

U.S. DOE SunShot Initiative – Concentrating Solar Power

On the Path to SunShot (2016)

- Update of original CSP SunShot Vision Study
- Significant CSP cost reductions realized since 2012
- Cost reductions driven primarily by solar field cost reductions and learning

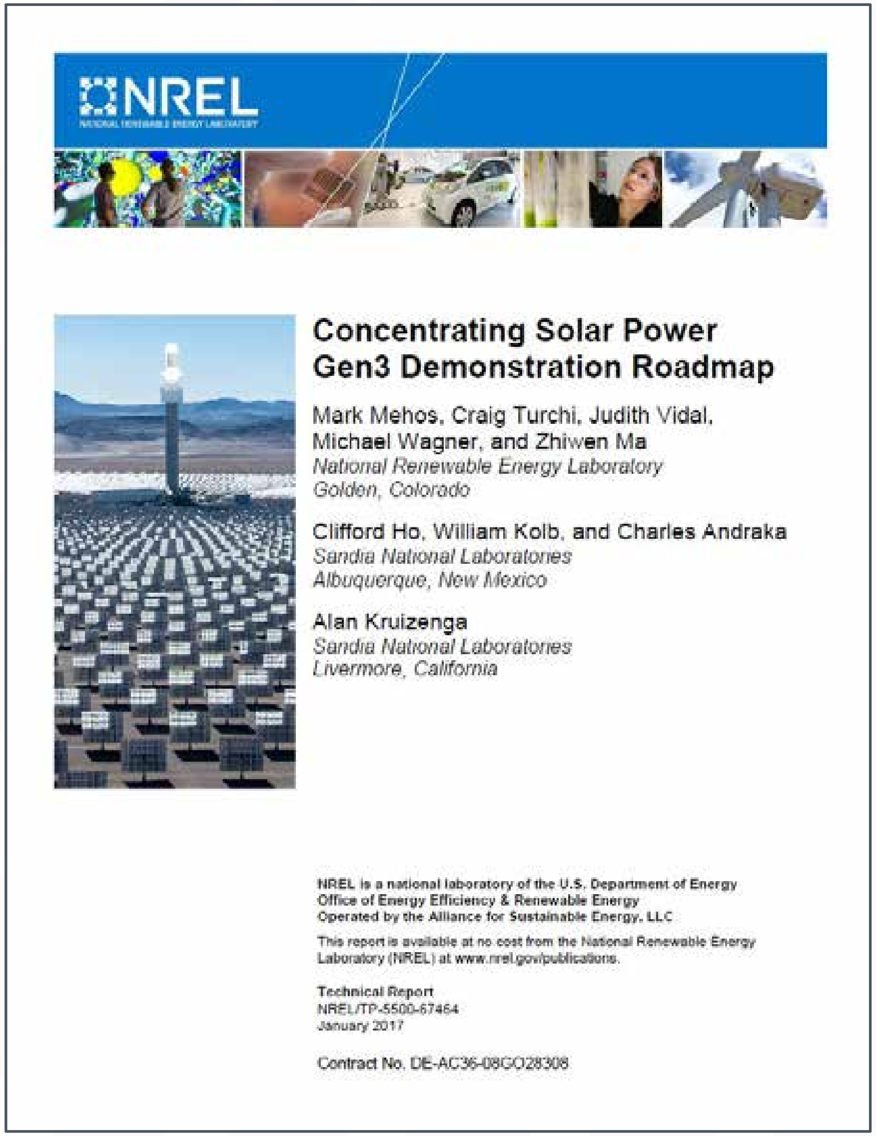




U.S. DOE SunShot Initiative – Concentrating Solar Power

CSP Gen3 Roadmap

- Identifies multiple pathways to achieve remaining performance gains and cost reductions
- Leverages DOE R&D support for high-temperature supercritical carbon dioxide (sCO_2) Brayton cycle



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Concentrating Solar Power Gen3 Demonstration Roadmap

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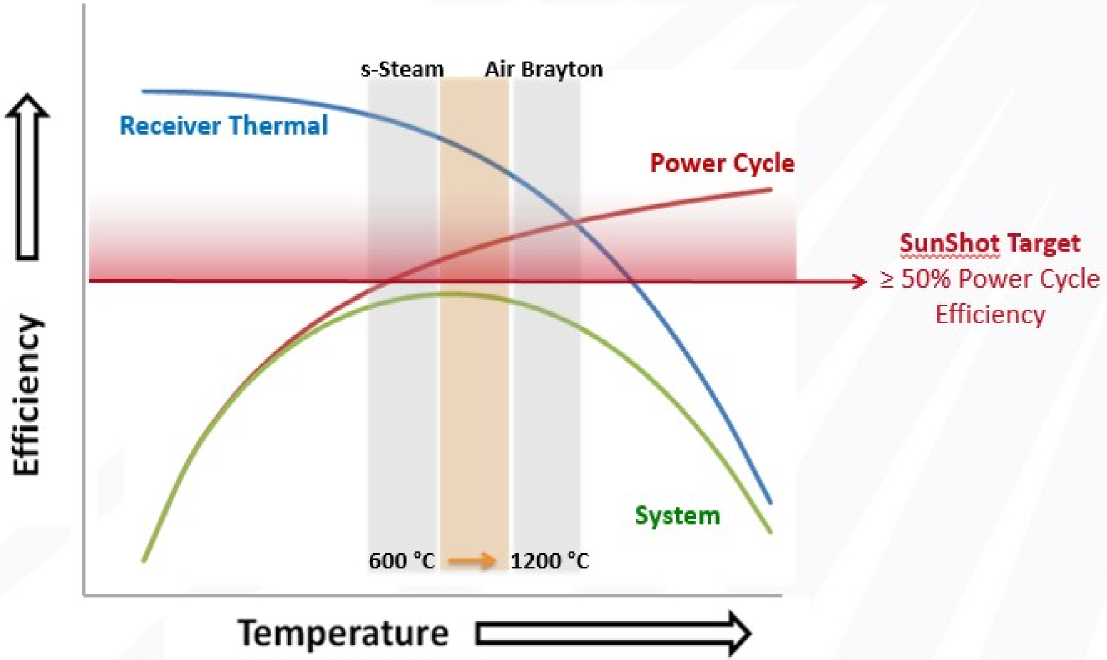
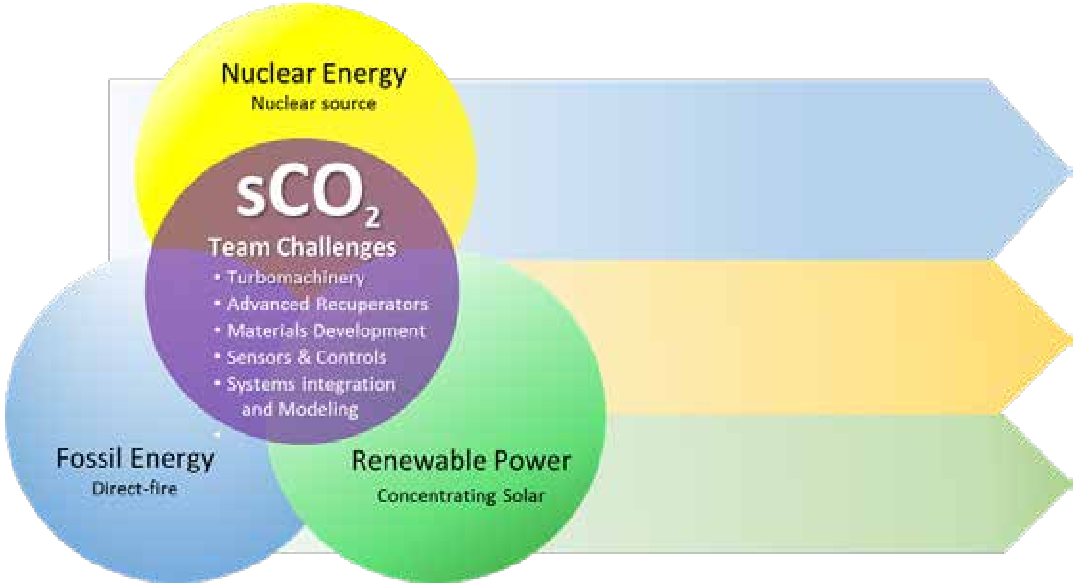
Third Generation CSP: 700 °C+

sCO_2 Power Cycles

- Can achieve η > 50% operating at >700ºC
- Scale from 50-500 MW and can scale to 10 MW with modest η decrease
- Suitable for dry cooling



Third Generation CSP: 700 °C+
Leveraging Cross-Cutting STEP Initiative



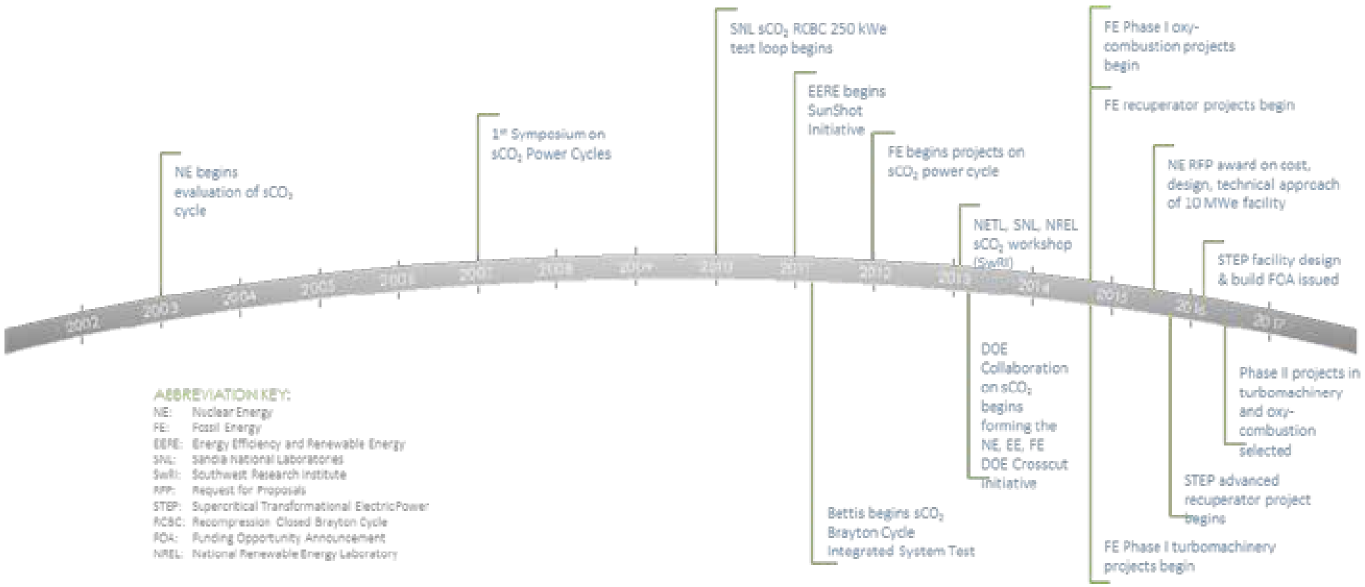
STEP Team Objectives

- Launch facilities to test and validate the technology

  2020 Operation
  Indirect-fired 10 MWe pilot facility

  2026 Operation
  Commercial-scale demonstration plant

- Demonstrate thermal cycle efficiency of > 50%
- Optimize performance and lower capital costs



CSP SunShot Pathways

Collector Field

- Cost <\$75/m^2
- Concentratio n ratio >50
- Operable in 35-mph winds
- Optical error <3.0 mrad
- 30-year lifetime

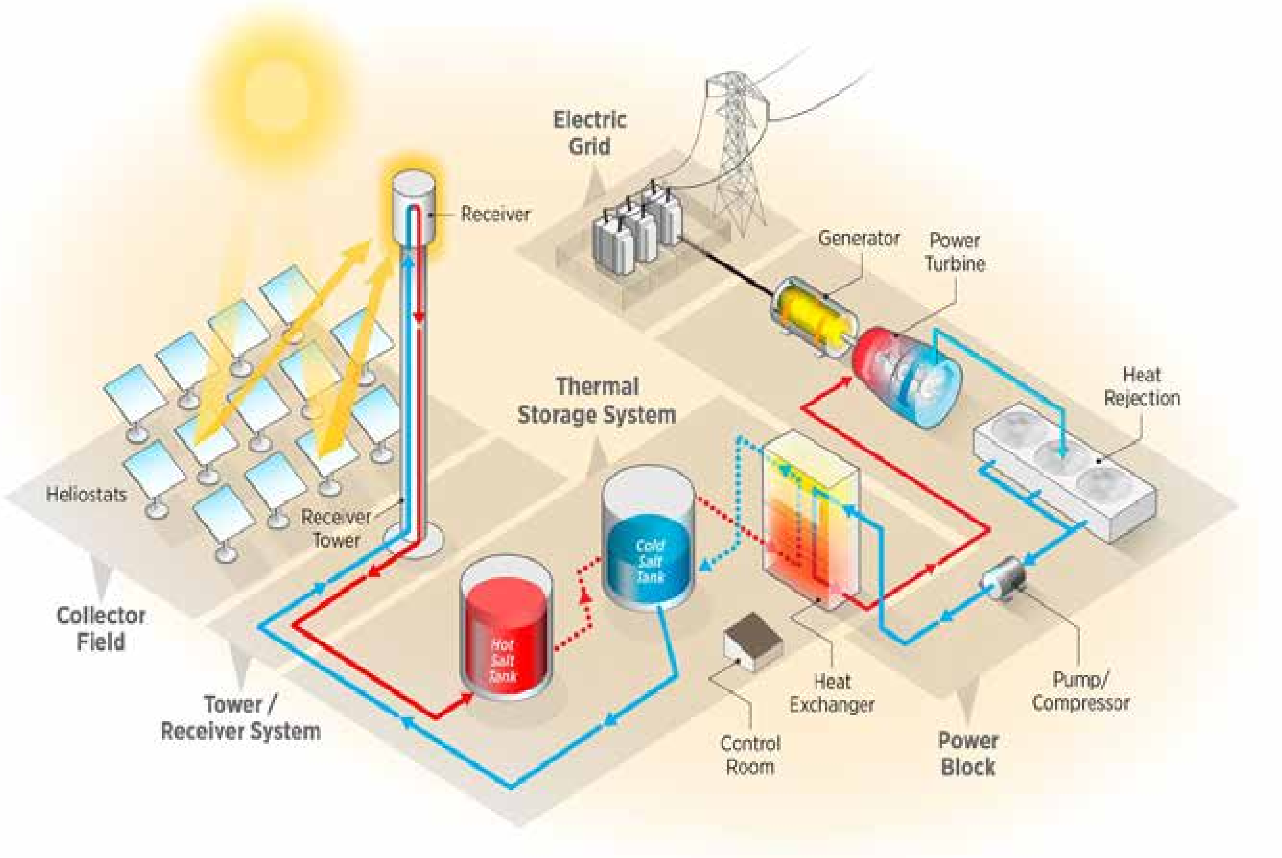
	Molten Salt	Falling Particle	Gas Phase
Receiver *Cost< $150/kWth* *Thermal Efficiency> 90%* *Exit Temperature> 720°C* *10,000 cycle lifetime*	• Similarities to prior demonstrations • Allowance for corrosive attack required	• Most challenging to achieve high thermal efficiency	• High-pressure fatigue challenges • Absorptivity control and thermal loss management
Material & Support *Cost< $1/kg* *Operable range from 250°C to 800°C*	• Potentially chloride or carbonate salt blends; ideal material not determined • Corrosion concerns dominate	• Suitable materials readily exist	• Minimize pressure drop • Corrosion risk retirement
Thermal Storage *Cost < $75/kWrh* *99% energetic efficiency* *95% exergetic efficiency*	• Direct or indirect storage may be superior	• Particles likely double as efficient sensible thermal storage	• Indirect storage required • Cost includes fluid to storage thermal exchange
HTF to sC02 Heat Exchanger	• Challenging to simultaneously handle corrosive attack and high-pressure working fluid	• Possibly greatest challenge • Cost and efficiency concerns dominate	• Not applicable

Supercritical C02 Brayton Cycle

- Net thermal-to-electric efficiency> 50%
- Power-cycle system cost< $900/kWe
- Dry-cooled heat sink at 40° C ambient
- Turbine inlet temperature 700°C

CSP SunShot Pathways

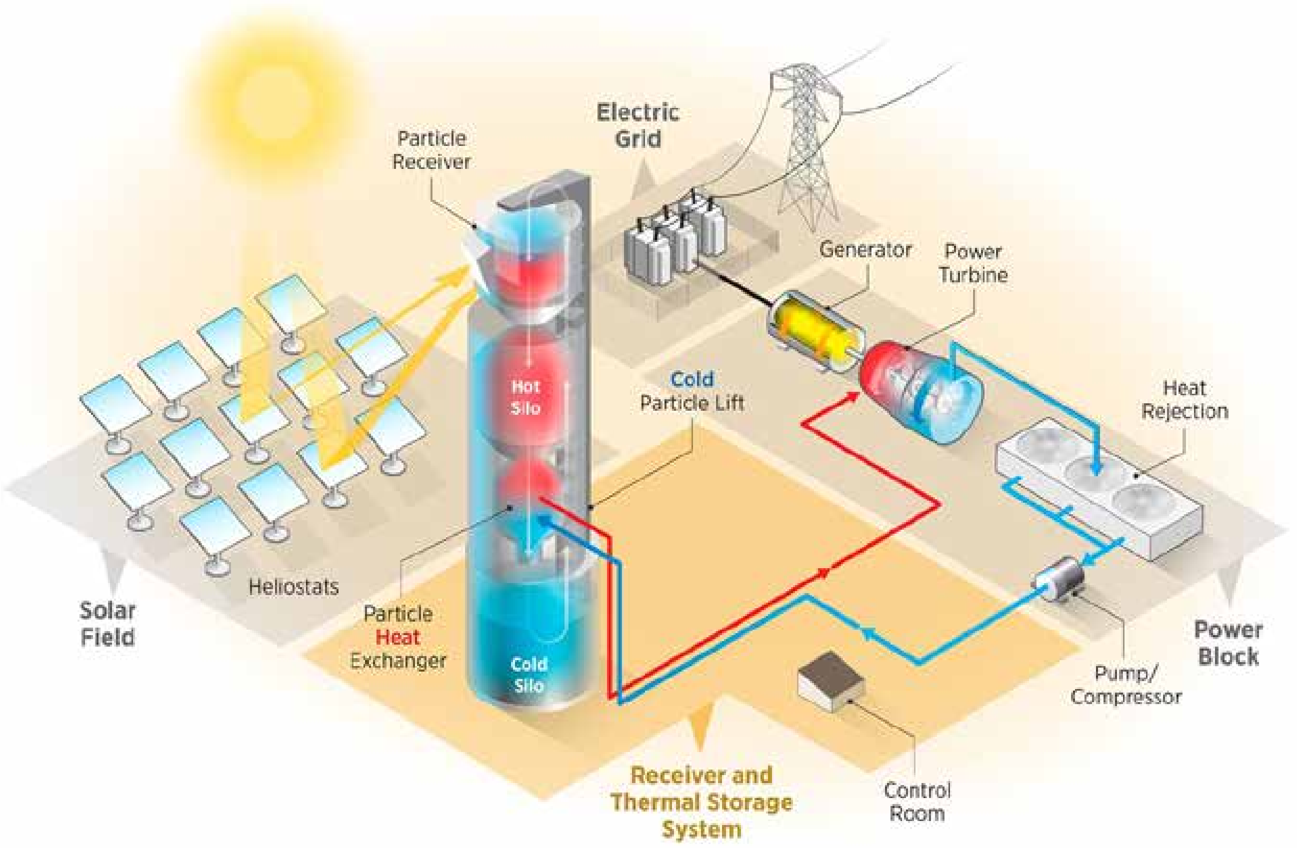
- Molten Salt
- Particle
- Gas-Phase



- Molten salt technology represents most familiar pathway toward Gen3 targets, e.g. receiver and TES design.
- Intermediate temperature salts (<650C) may provide opportunity for near-term deployment.
- Development of high-temperature salts and compatible containment materials represent highest priority R&D challenges.

CSP SunShot Pathways

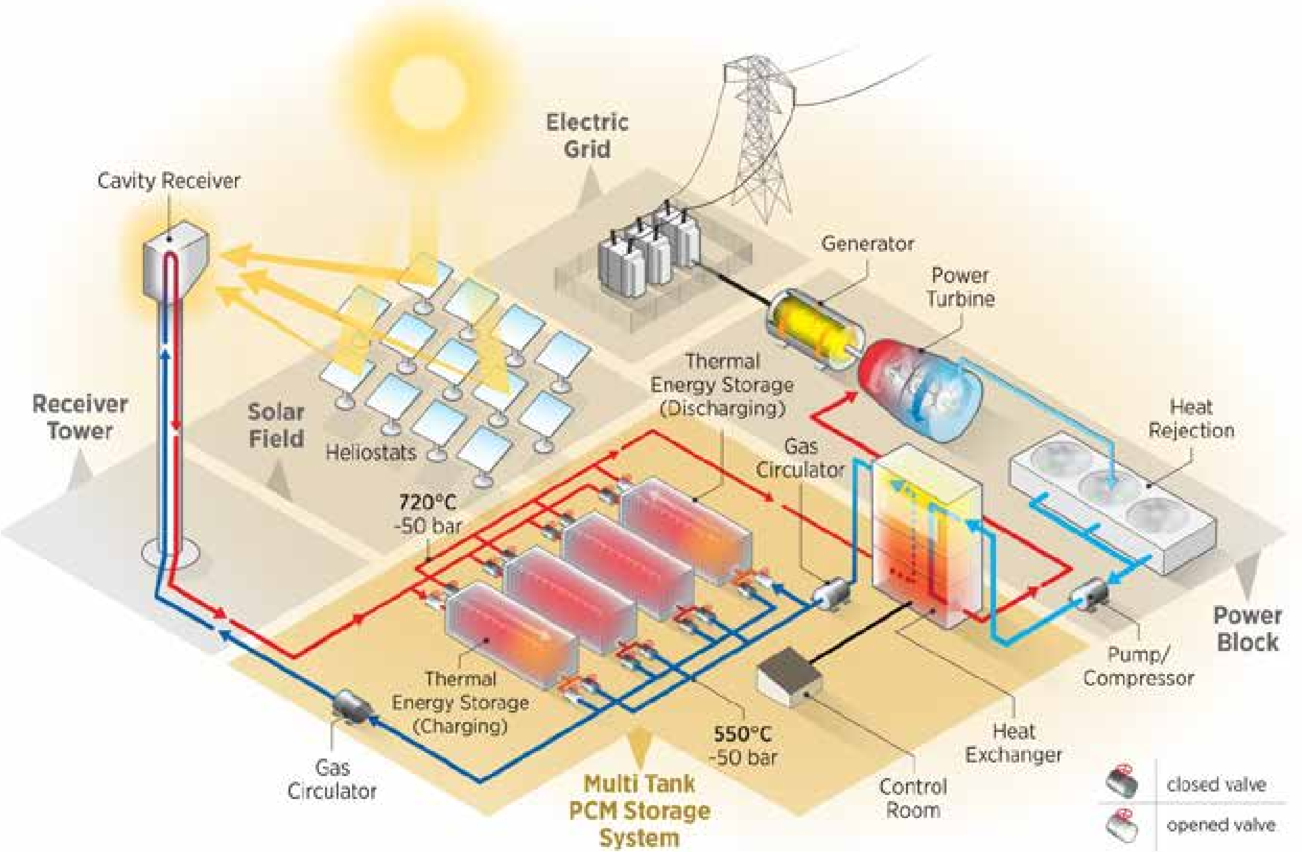
- Molten Salt
- Particle
- Gas-Phase



- Particle-based systems can avoid degradation and corrosion challenges associated with advanced high-temperature molten salt systems.
- Many BOS components, e.g. particle HXs, storage, and conveyance, have been developed by industry for alternative applications.
- Primary challenges include efficient heating of particles through direct or indirect solar illumination , flow control, and containment.

CSP SunShot Pathways

- Molten Salt
- Particle
- Gas-Phase



- Primary advantages include gas-phase stability over broad temperature range of operation, low HTF corrosivity, and simplicity of gaseous HTF-to-sCO2 heat exchangers.
- Several gas-phase receiver designs indicate thermal efficiencies >90% are achievable.
- Challenges include inferior heat transfer characteristics and relative immaturity of compatible TES and integration approaches relative to other pathways.

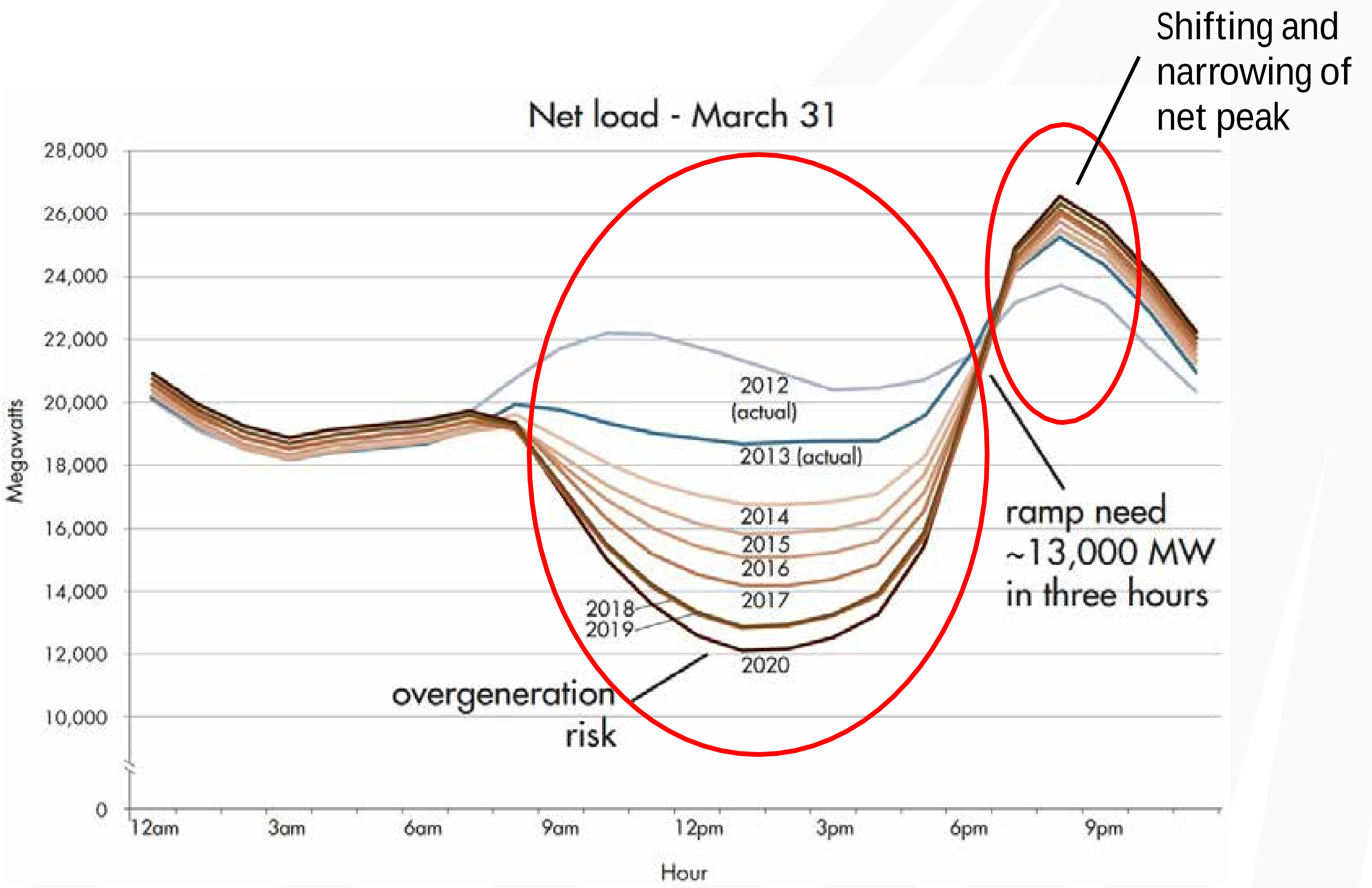
Discussion

- U.S. SunShot Overview
- Understanding the Value of CSP with Thermal Energy Storage

Beyond Levelized Cost of Energy

- Competition with PV is often viewed based on LCOE (or power purchase price)
- The dispatchability of CSP with TES provides value not captured by a simple LCOE calculation
- There is a need to educate utilities, regulators, and researcher organizations on proper methods for evaluating and maximizing the benefits of CSP

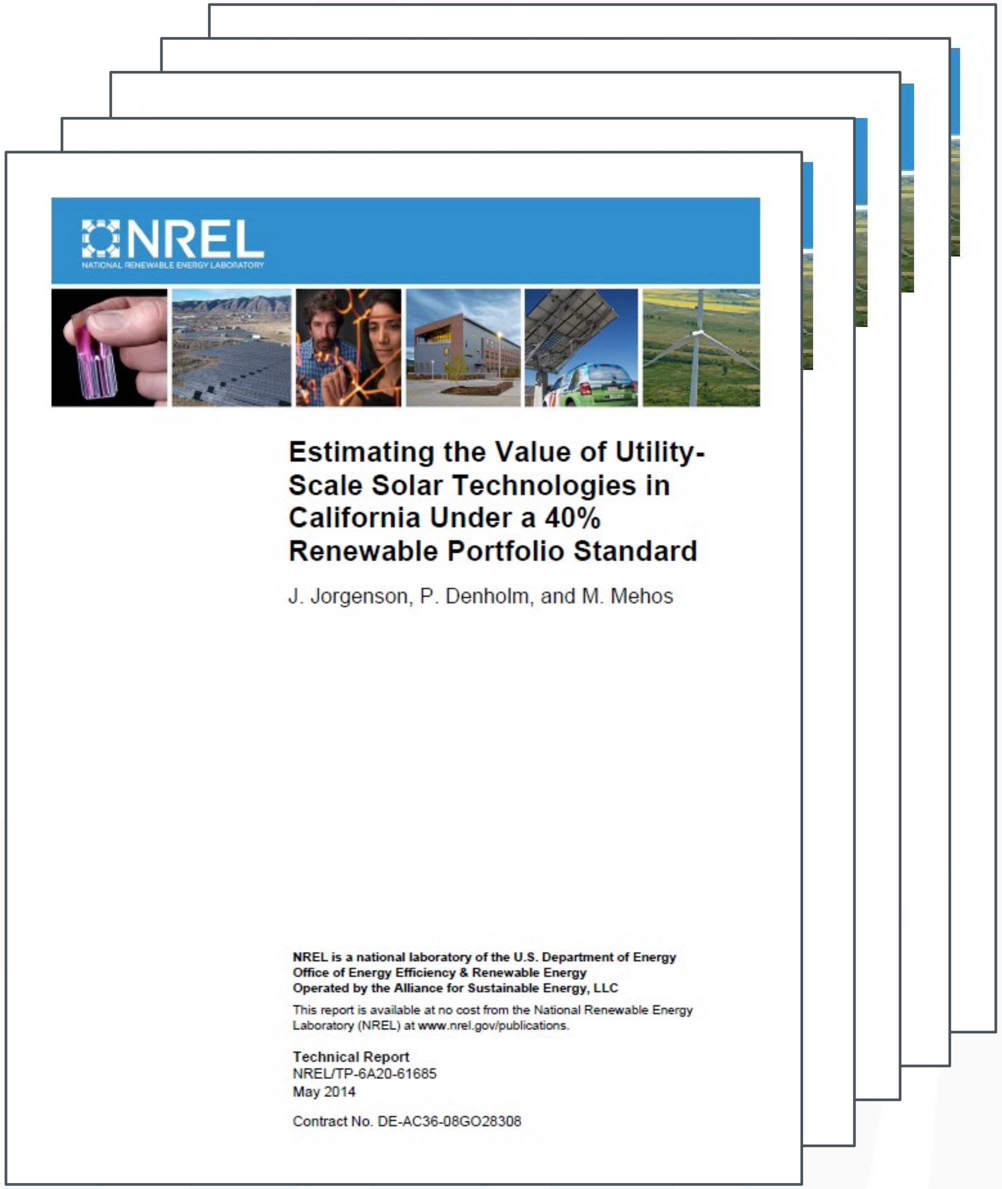
CAISO Duck Curve – Circa 2013



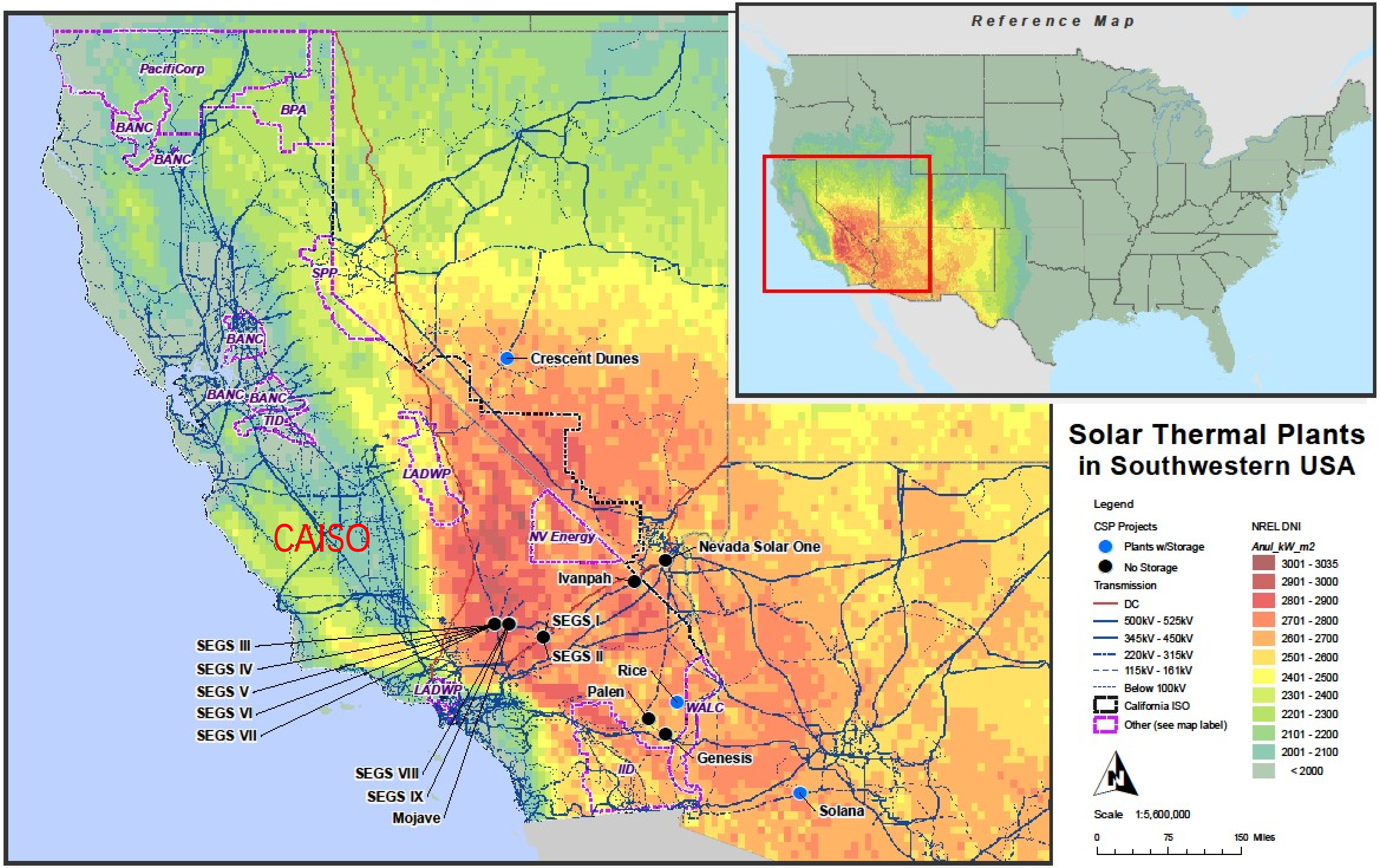
Quantifying the Benefits of CSP with Thermal Energy Storage

- Colorado "Test" System
- California/WECC

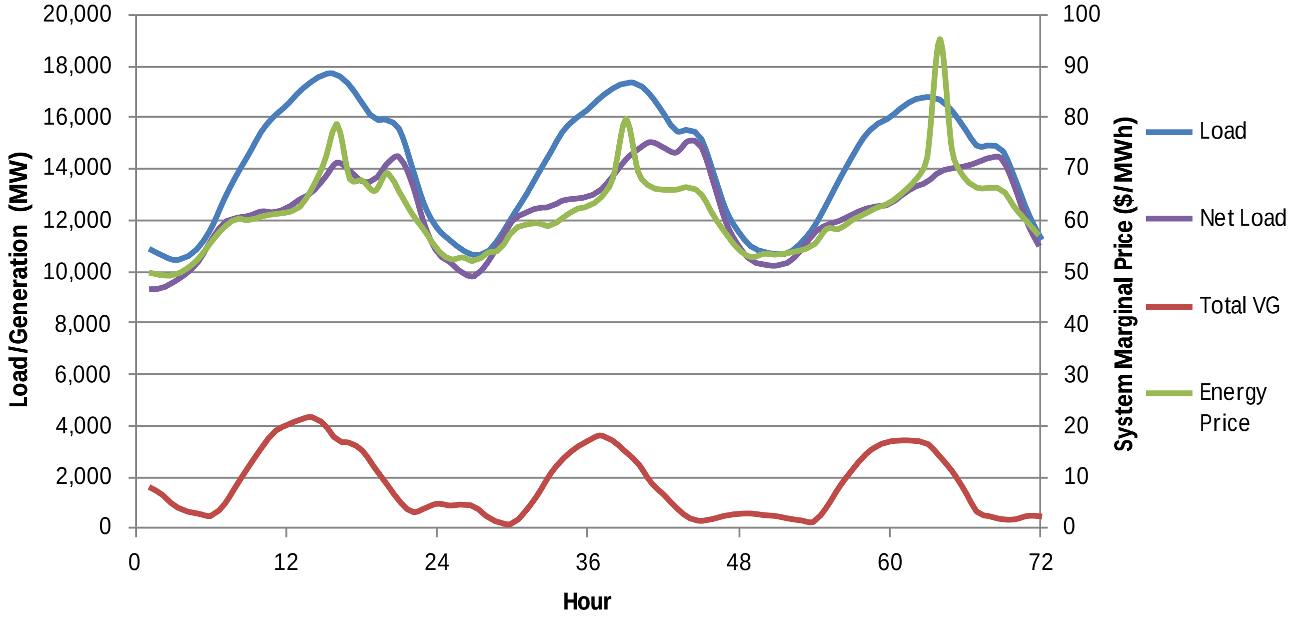
http://www.nrel.gov/publications



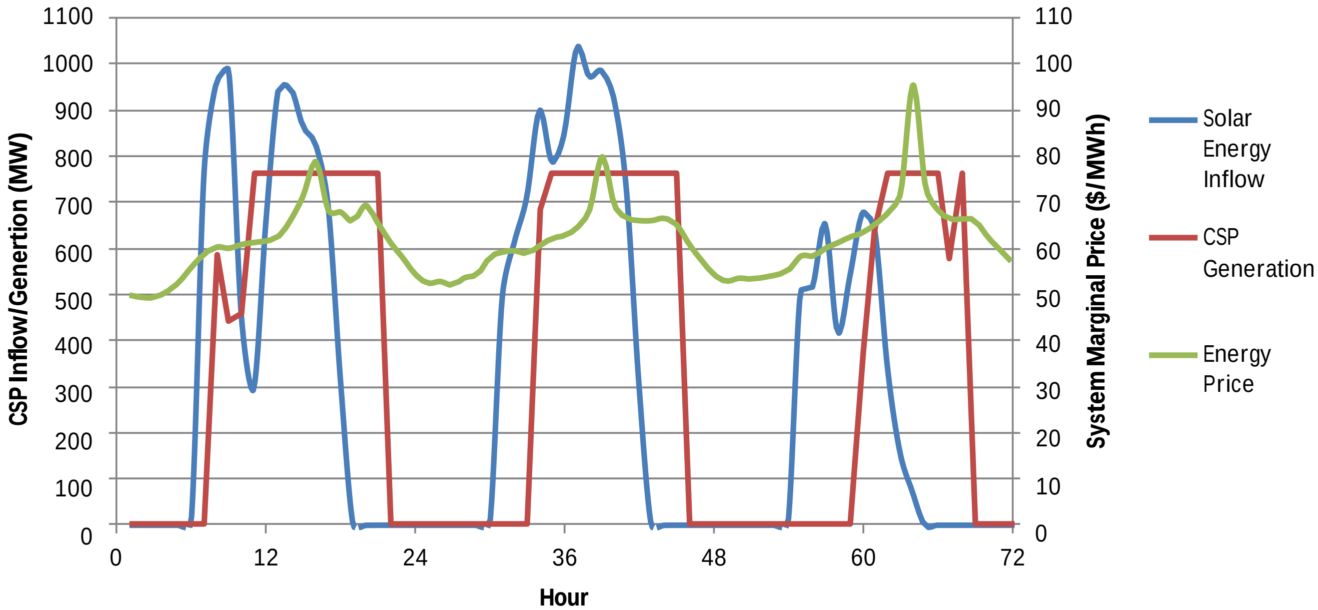
Analysis of Operational and Capacity Benefits of CSP in Southwest Balancing Area



June Price and Dispatch

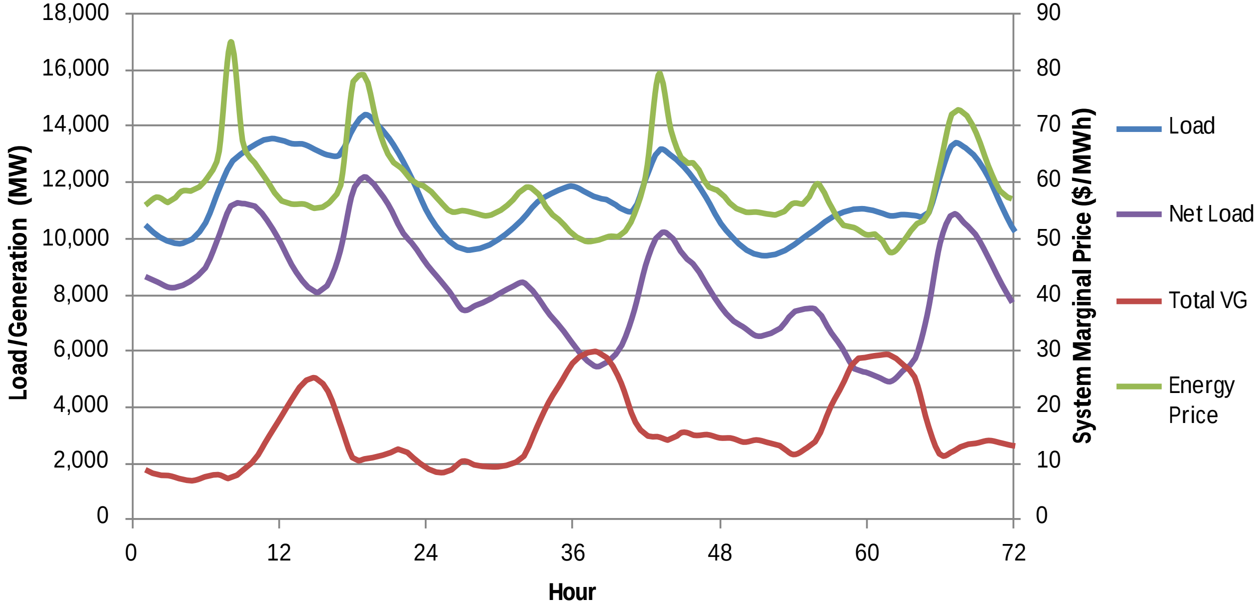


System net load and marginal price for June 24–26

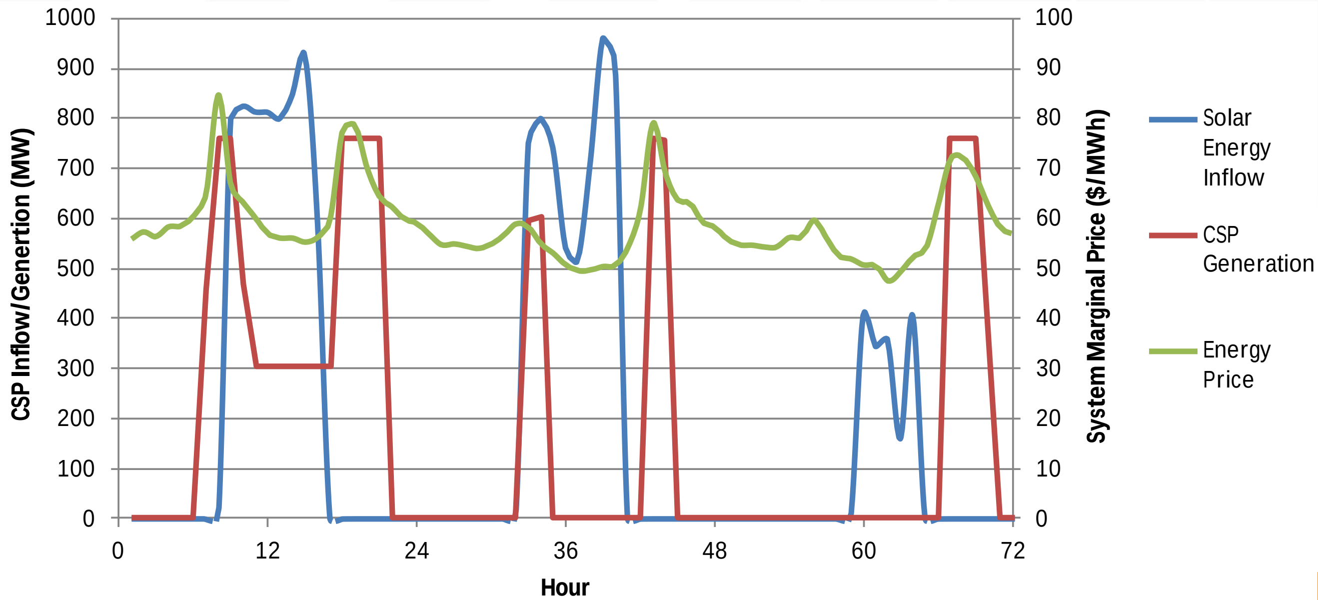


System marginal price and corresponding CSP generation on June 24–26

January Price and Dispatch



System net load and marginal price for January 31–February 2



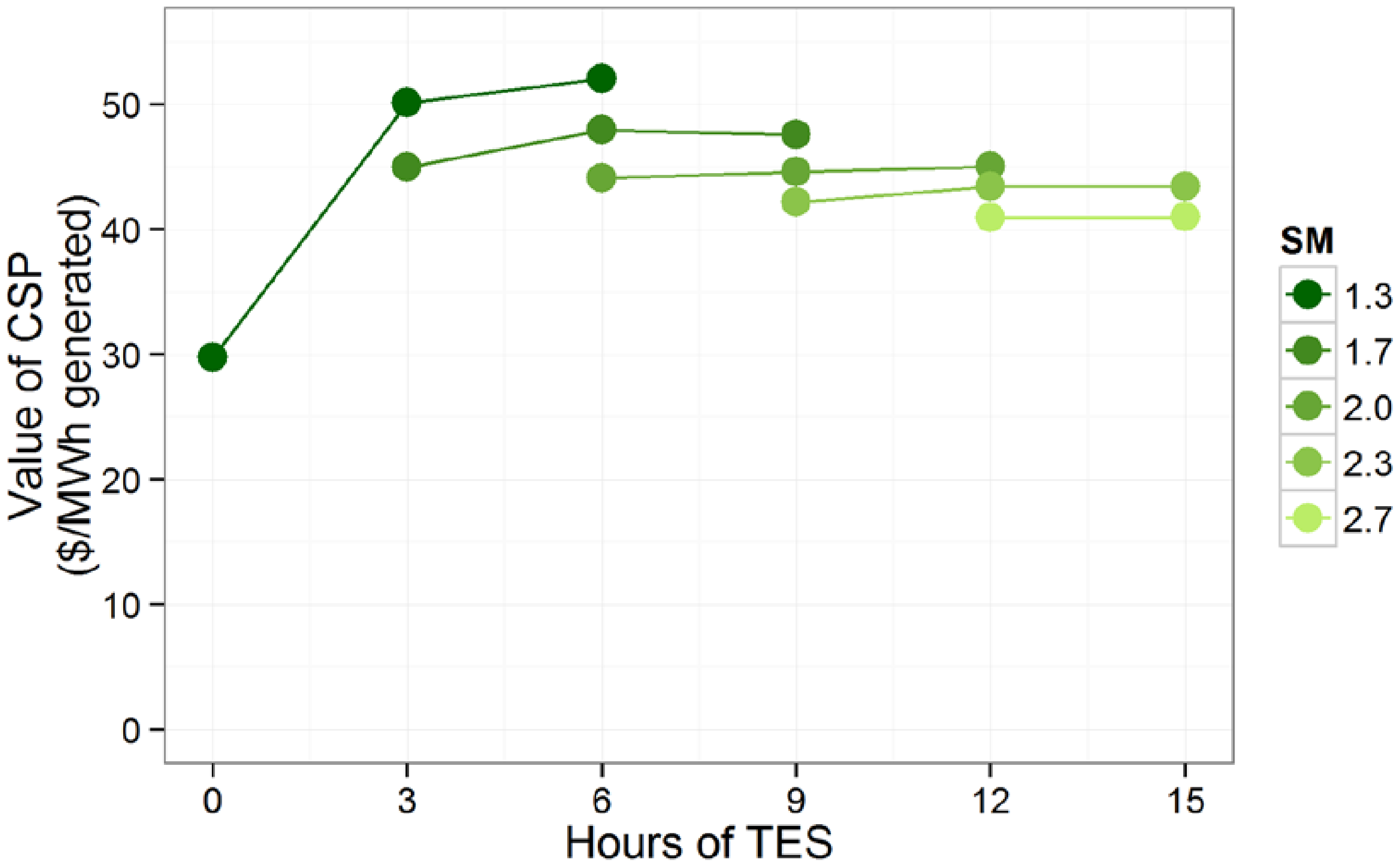
System marginal price and corresponding CSP generation on January 31–February 2

California ISO Analysis – 33% Renewable Portfolio Standard

Relative to PV, CSP provides additional operational Value to California grid

	Marginal Operational Value ($/MWh)	
	CSP-TES (SM = 1.3, 6 hrs TES)	**PV**
Displaced Fuel	40.2	27.8
Displaced Emissions	10.3	3.1
Reduced Startup & Shutdown	1.6	-0.6
Reduced Variable O&M	0.4	1.2
Total	**52.7**	**31.6**

CAISO Analysis – Operational Value



Lowest solar multiples (lower annual capacity factors) yield the highest operational system value

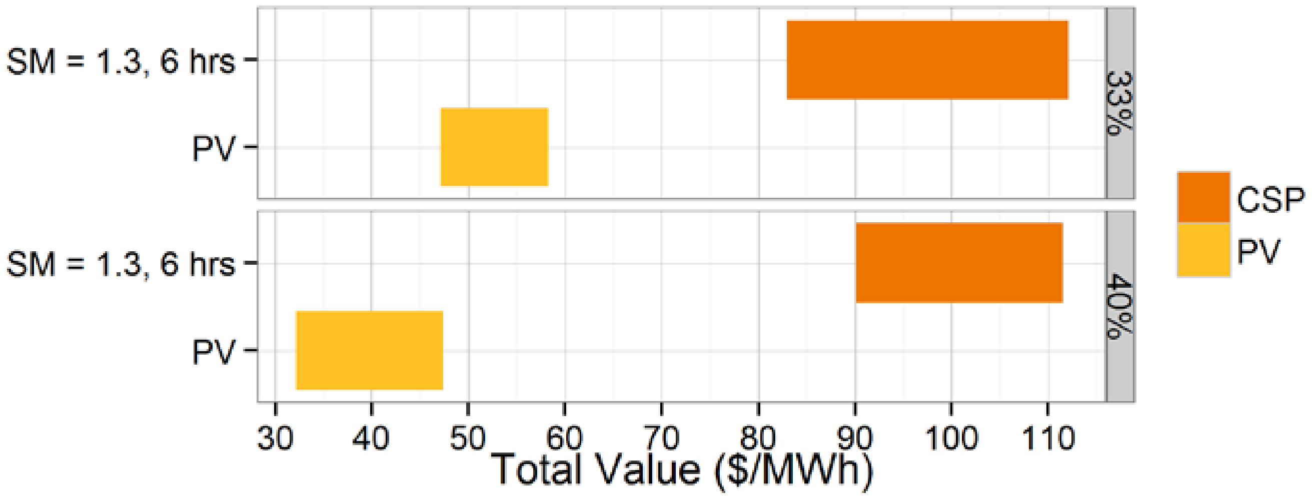
CAISO Analysis – Capacity Value

CSP integrated with thermal energy storage maintains high capacity value

	Capacity Credit (%)	
	CSP-TES (with > 3 Hrs Storage)	PV
33% RPS Scenario	92.2%	22%
40% RPS Scenario	96.6%	3.4%

CAISO Analysis – Total Valuation

- Relative value of CSP is $48/MWh greater than PV in the 33% scenario and about $63/MWh greater in the 40% scenario



Summary

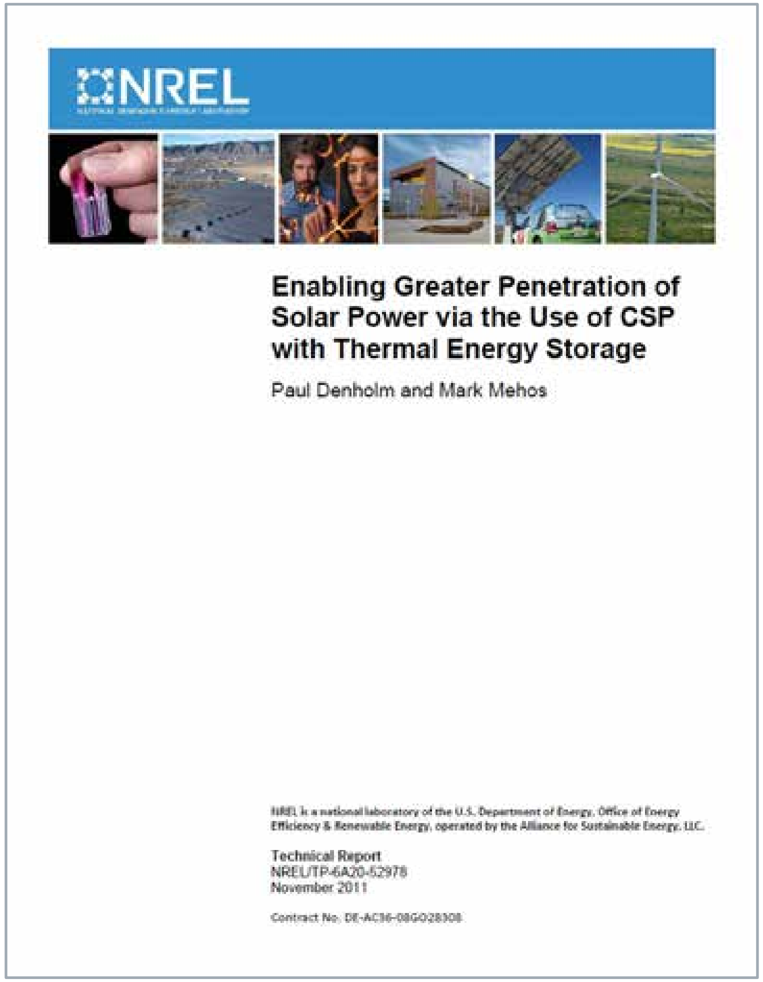
- CSP costs have fallen dramatically, driven primarily by learning and solar field cost reductions.
- Additional cost reductions are foreseen, driven by additional learning and integration with advanced thermodynamic cycles.
- LCOE is an incomplete metric when considering the value of dispatchable CSP.
- Operational flexibility and dispatchability add considerable value to CSP generation.
- Under conditions of high-penetrations of variable generation technologies, the value of CSP can be 5-6 cents/kwh higher than PV.
- Net system benefit, not discussed today, is recommended for side-by-side comparisons of CSP with other generation technologies.

Thank you!

Questions?

Synergistic Benefits of PV and CSP with Thermal Energy Storage

Investigated the impact of CSP w/ thermal energy storage as an enabling technology for high penetrations of solar (PV and CSP).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Enabling Greater Penetration of Solar Power via the Use of CSP with Thermal Energy Storage

Paul Denholm and Mark Mehos

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-6A20-52978
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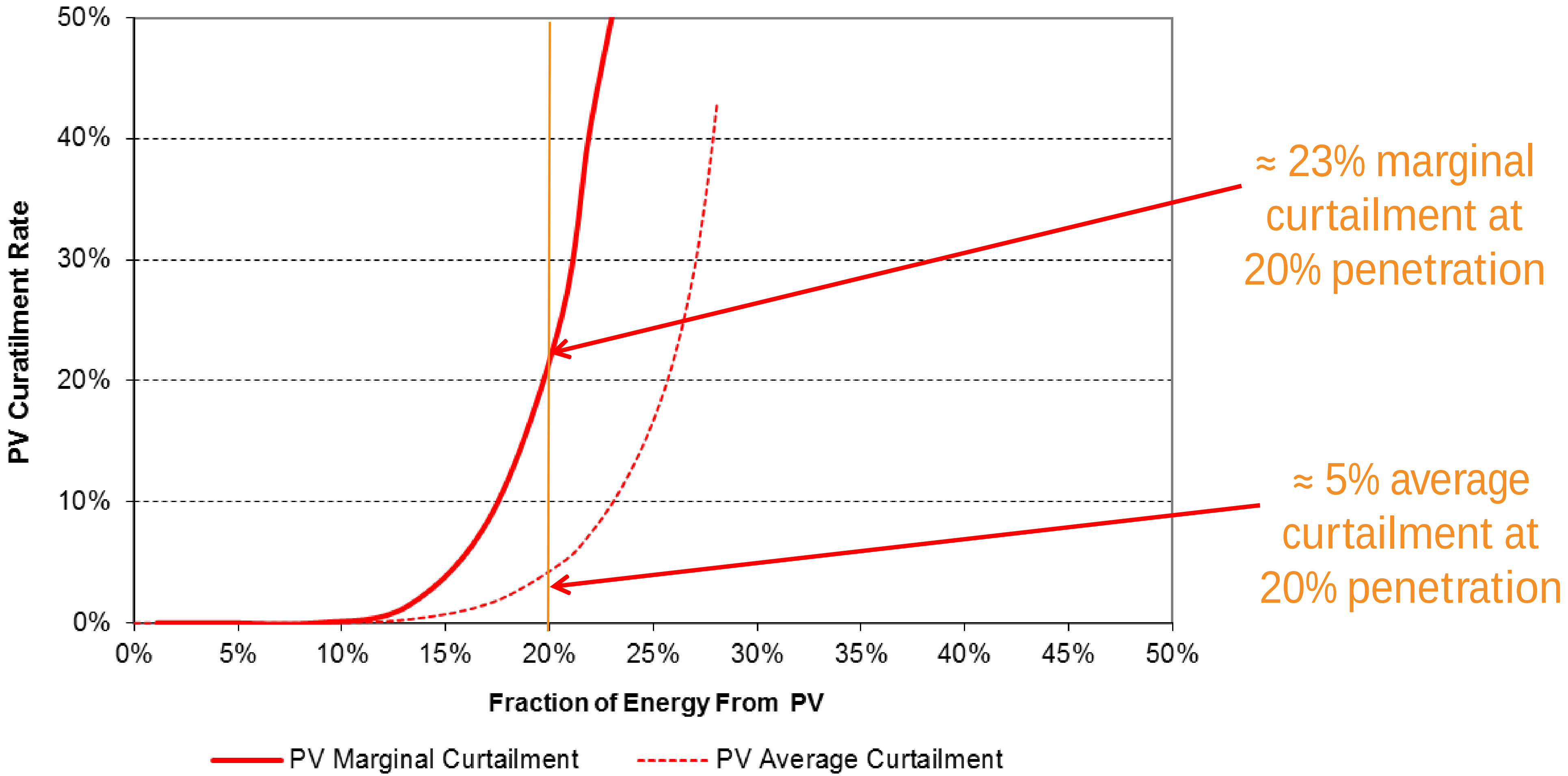
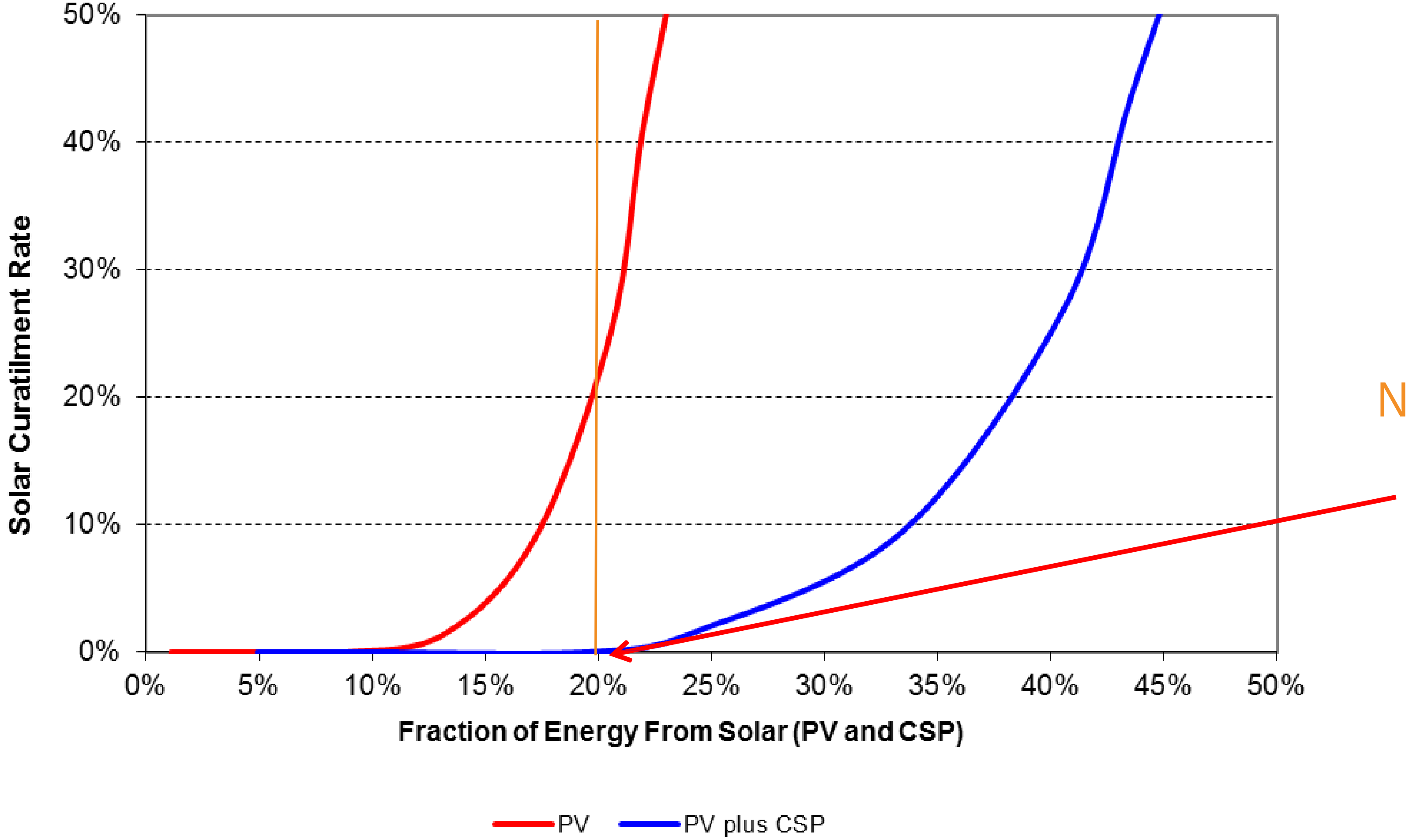
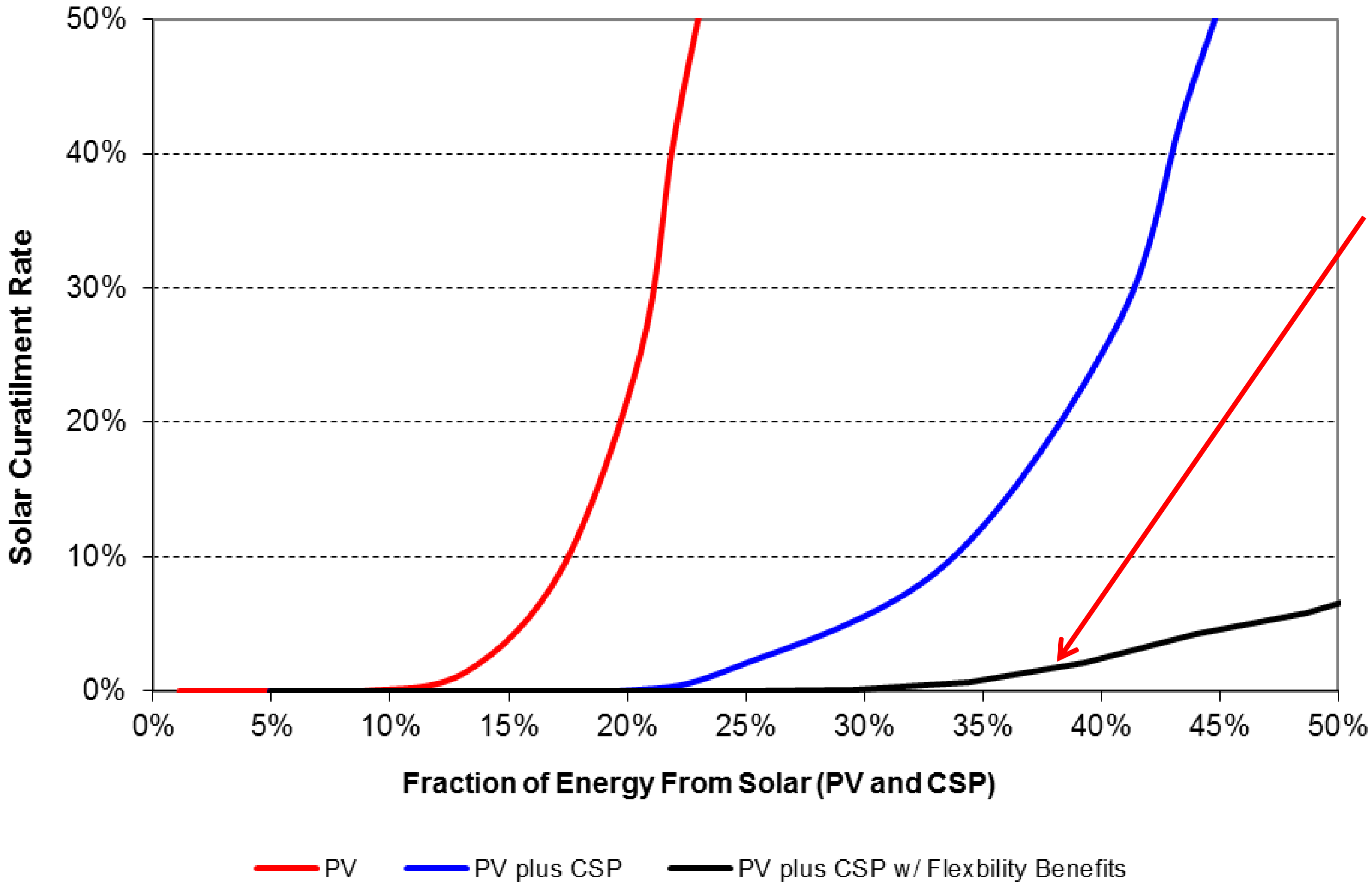
Contract No. DE-AC36-08GO28308

Average and marginal curtailment rates of PV in base scenario





No curtailment at 20% Solar Penetration

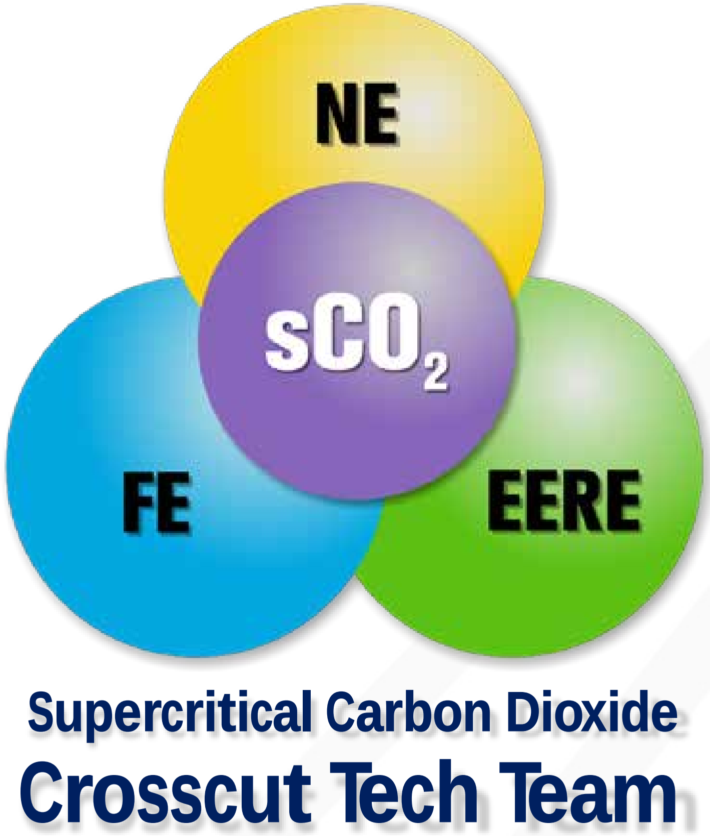


Low curtailment at
30% solar penetration

Common FE, NE, EERE Application Space

Application	Size [MWe]	Temperature [°C]	Pressure [MPa]
Nuclear (NE)	10 – 300	350 – 700	20 – 35
Fossil Fuel (FE) (Indirect heating)	300 – 600	550 – 900	15 – 35
Fossil Fuel (FE) (Direct heating)	300 – 600	1100 – 1500	35
Concentrating Solar Power (EERE)	10 – 100	500 – 1000	35
Shipboard Propulsion	<10 – 10	200 – 300	15 – 25
Waste Heat Recovery (FE)	1 – 10	< 230 – 650	15 – 35
Geothermal (EERE)	1 – 50	100 – 300	15

DOE sCO2 Crosscut Initiative: R&D



Pillar	Objective	Participant
R&D	• Accelerate technology development • Improve performance and cost	• Universities • National Labs • Industry • International collaboration
STEP (**S**uper-critical CO_2 **T**echnology **E**lectric **P**ower) 10 MWe demo	• Test system performance under steady and transient conditions • Validate component performance • Reconfigure for applications, test next-generation components, optimize performance	• STEP facility team • Component OEM • Other collaboration
Demo	• Demonstrate commercial viability	• Industry